



CORE



Session 1, S40

Recent Progress of Beyond EUV (BEUV) Sources

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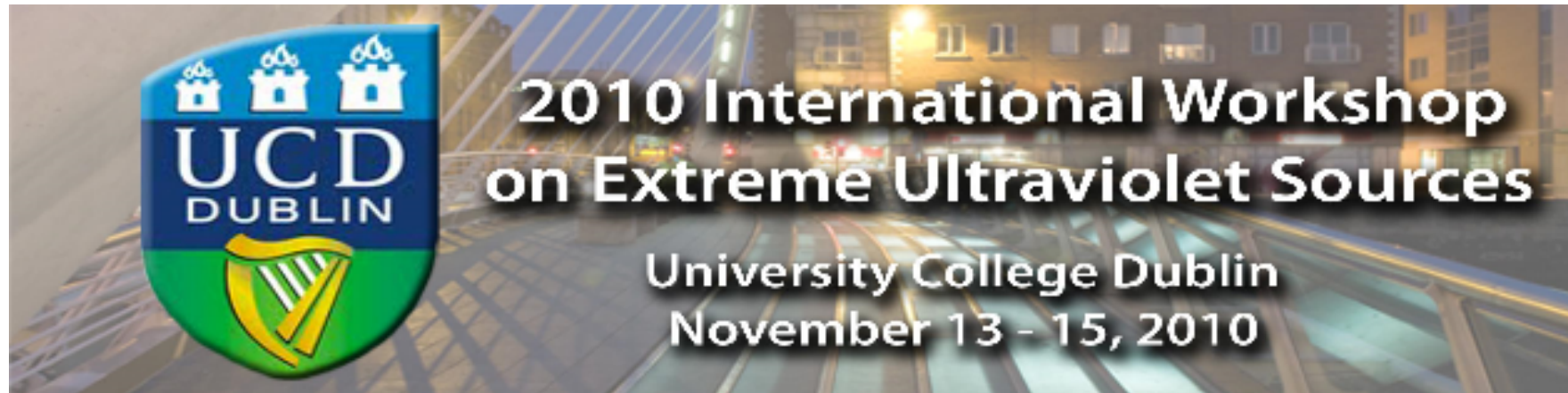
2011 International Workshop on EUV and Soft X-Ray Sources

Dublin, Ireland

Tuesday, November 8, 2011

Why 6.X nm EUV source?

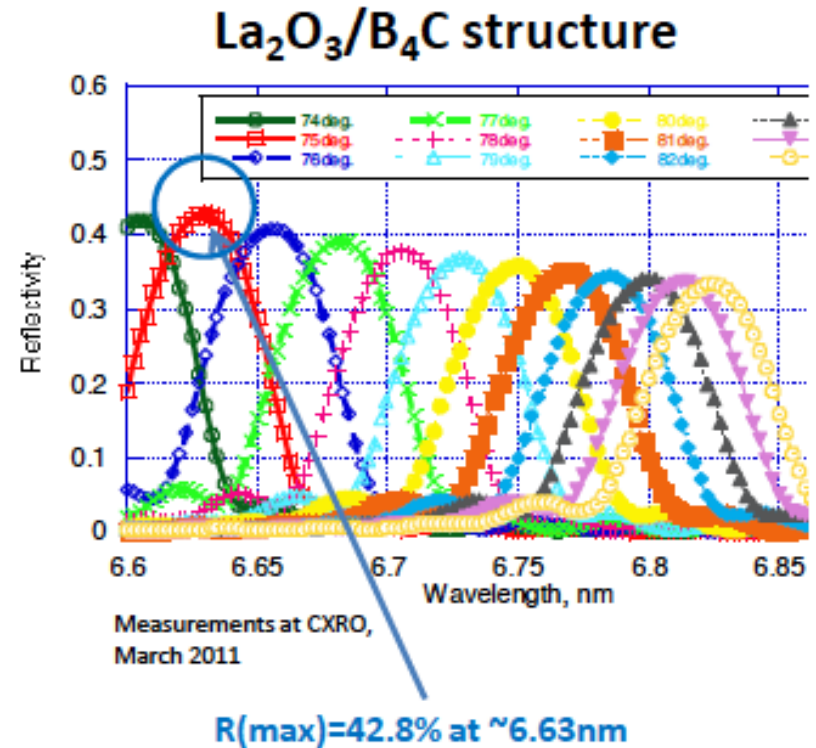
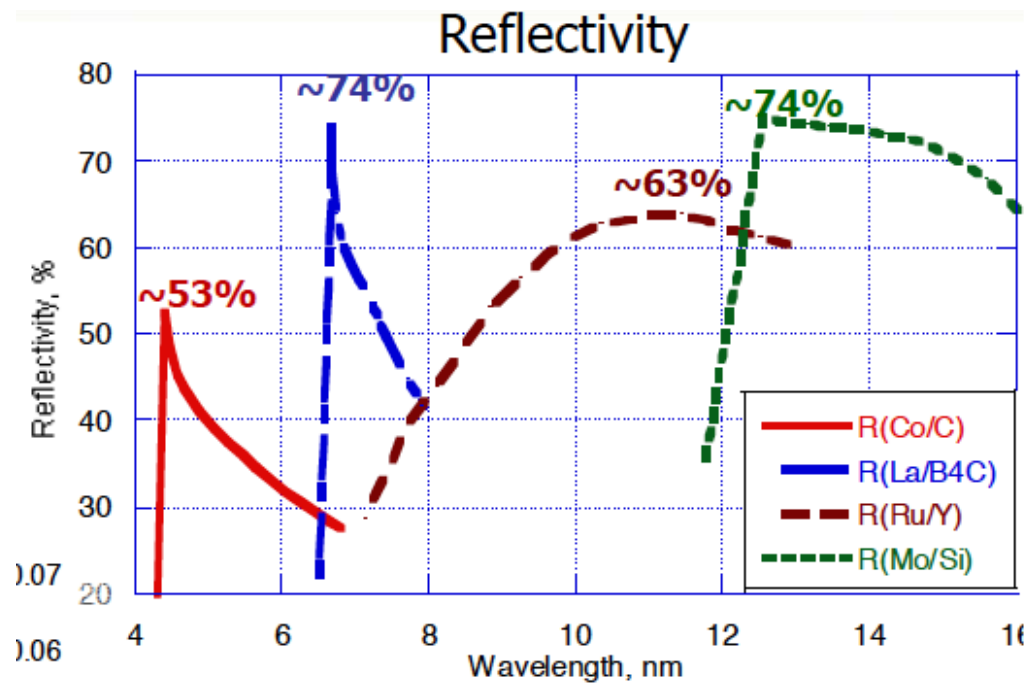
Beyond EUV (BEUV) source



From ASML presentation shows as follows:

- (1) extensive (beyond 8 nm@~2017)
- (2) **6.X nm choice: Best transmission & Easier Manufacturing**
- (3) Source: New fuel is needed (Gd and/or Tb, other???)
- (4) $R \sim 80\%$ (cal), $R \sim 40\%$ (exp)@La/B₄C MLM
- (5) **Optical throughput for 6.7 nm & 13.5 nm is comparable!!!**

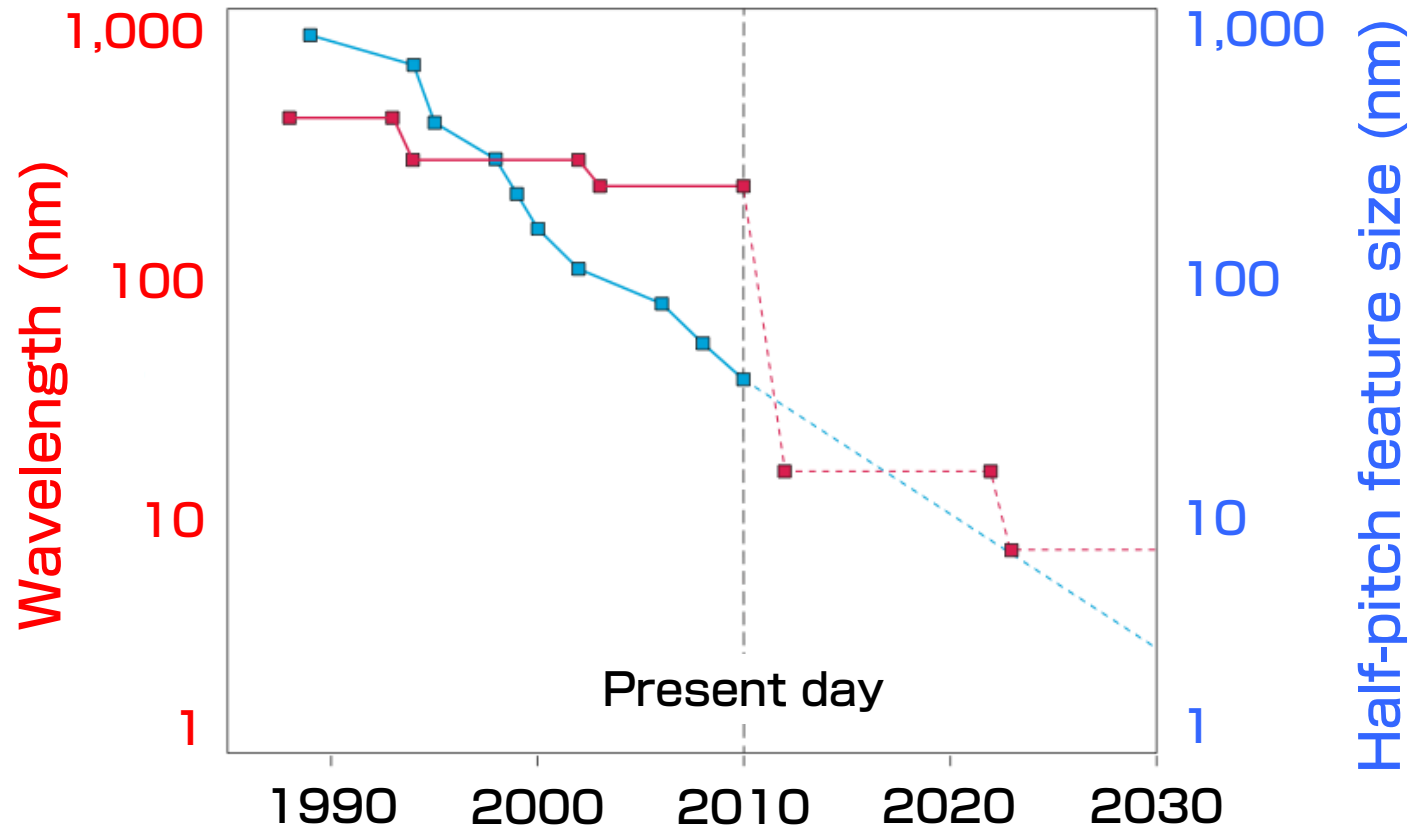
MLM for 6.X nm



Y. Platonov,
Proc. of 2010 IW on EUV Sources
(EUV Litho Inc., Dublin, Ireland, 2010).

Why 6.X nm EUV source?

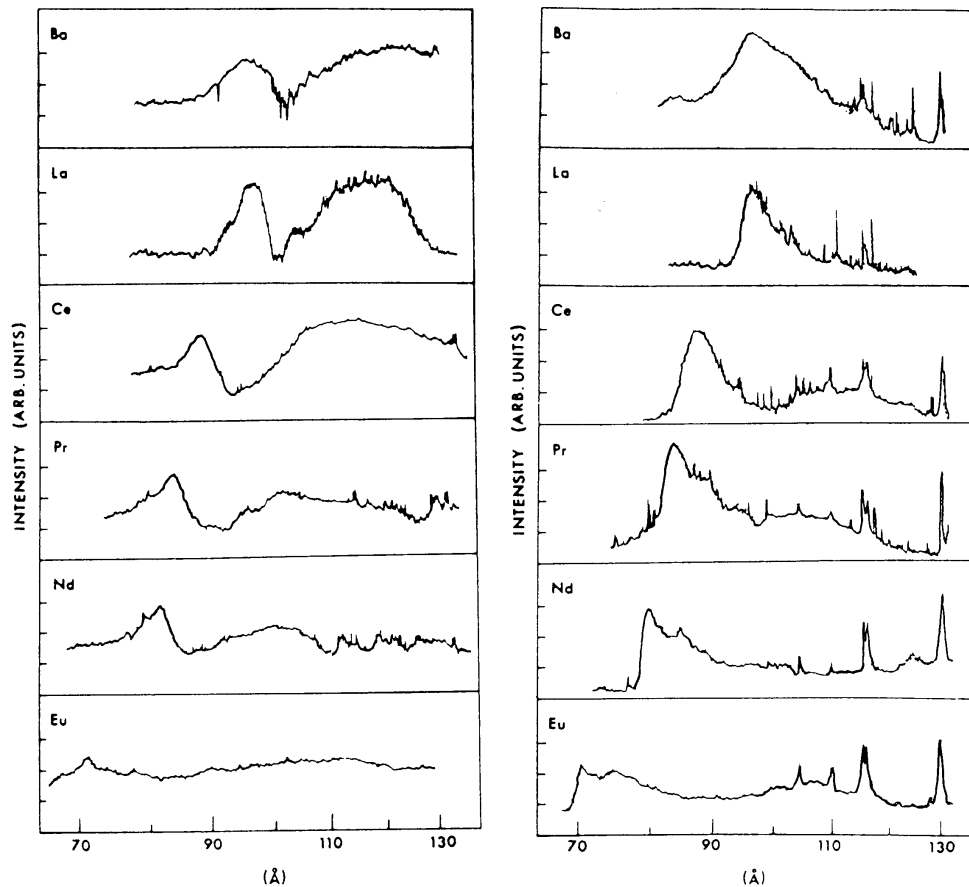
Beyond EUV (BEUV) source



First demonstration by Prof. O'Sullivan ($Z > 50$)

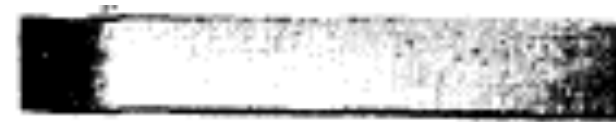
Spectra from elements with $Z > 50$ contain lines and an intense UTA due to $4p^6 4d^n - 4p^5 4d^n + 1 + 4d^n - 14f$ ($0 \leq n \leq 9$) transitions. The effects of CI are to cause a transitions in successive ion stages to overlap in energy.

The degree of overlap improves with Z up to $Z = 62$.



PRA25, 275 (1982)

for absorption spectroscopy



Gd

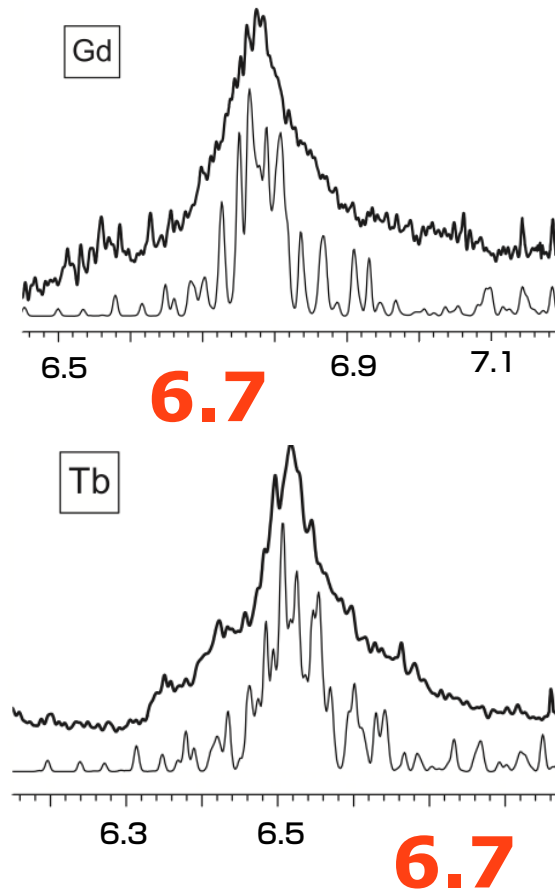


Metal Targets

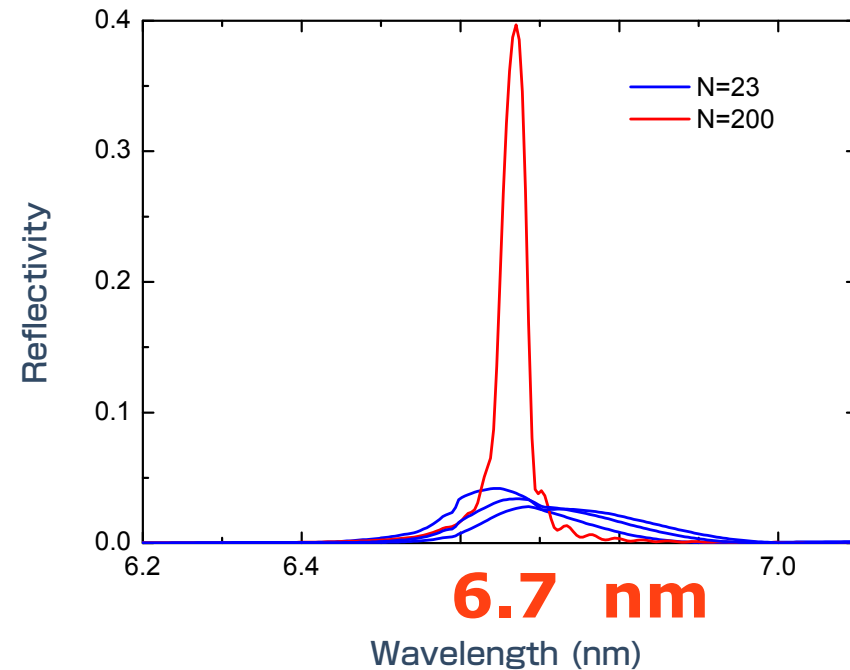
Salt Targets

Introduction... from previous spectral reports

6.7 nm: Gd, Tb plasmas



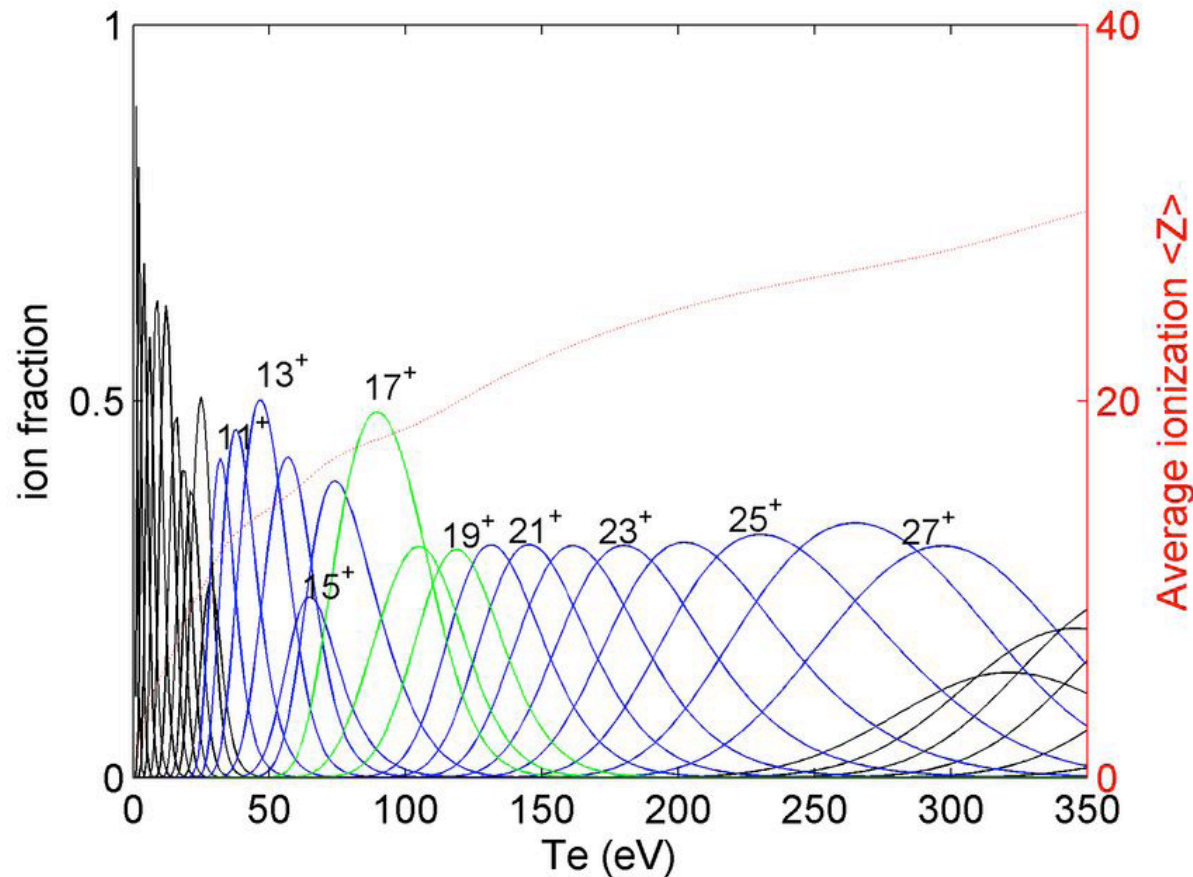
Mo/B₄C mirror



S. S. Churilov *et al.*, Phys. Scr. **80**, 045303 (2009).

Ionic population of Gd ions

We should produce 100 eV plasma.



T. Otsuka *et al.*, Appl. Phys. Lett. **97**, 111503 (2010).
B. Li *et al.* Appl. Phys. Lett. (to appear in 2011).

Physical summary for high-Z plasmas from 13.5-nm Sn plasmas

Optically thin plasmas for reducing self-absorption effects

Suppression of satellite emission & higher spectral purity

Long wavelength (low critical density): CO₂ laser@10¹⁹ /cc

Short laser pulse duration: ~1-2 ns@YAG laser (1064 nm)

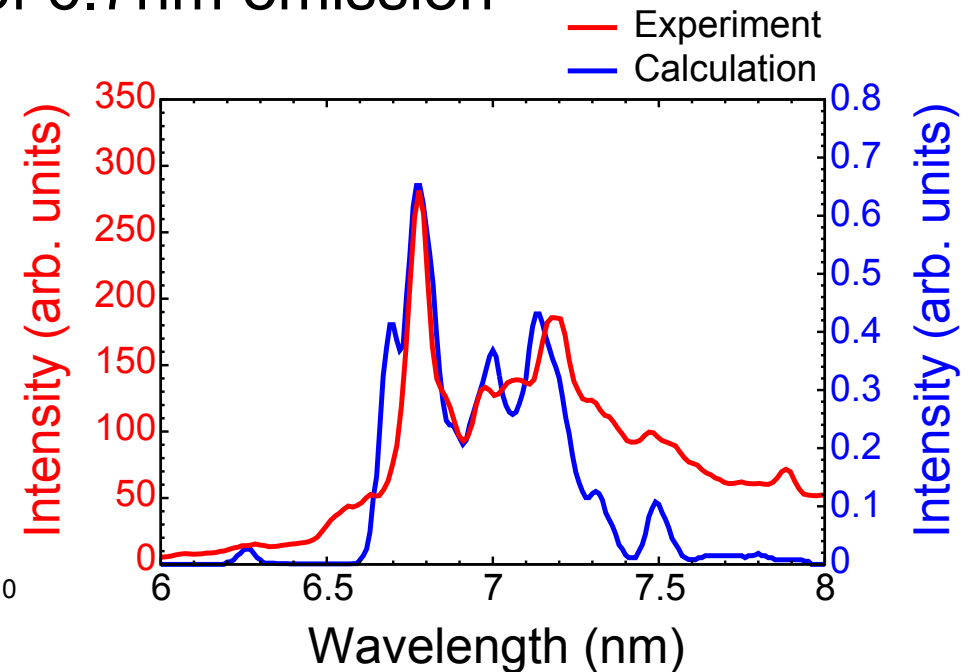
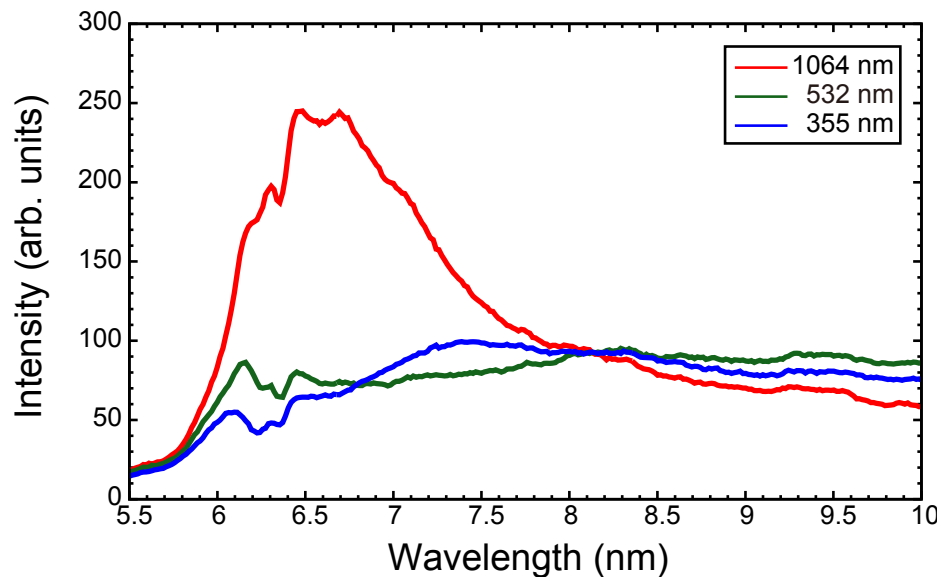
Low density targets

Discharge plasmas (low density plasmas)

Last Hawaii

What's new: for high power and high CE

- Laser color dependence
- Resonant line appearance in low-density plasma
- Enhancing conditions of 6.7nm emission



T. Otsuka *et al.*, APL **97**, 111503 (2010).

T. Otsuka *et al.*, APL **97**, 231503 (2010).

Question

- CE and spectral behavior for fs, ps, and ns
- High temperature (30-50 eV to 50-150 eV):
high energy particle generation?

Objective

We demonstrate an efficient BEUV source at 6.7 nm by rare-earth (Gd) LPP and DPP in a fundamental research point of view .

Physical summary for high-Z plasmas for 6.7-nm Gd plasmas

Optical thin plasmas for reducing self-absorption effects

Suppression of satellite emission & higher spectral purity

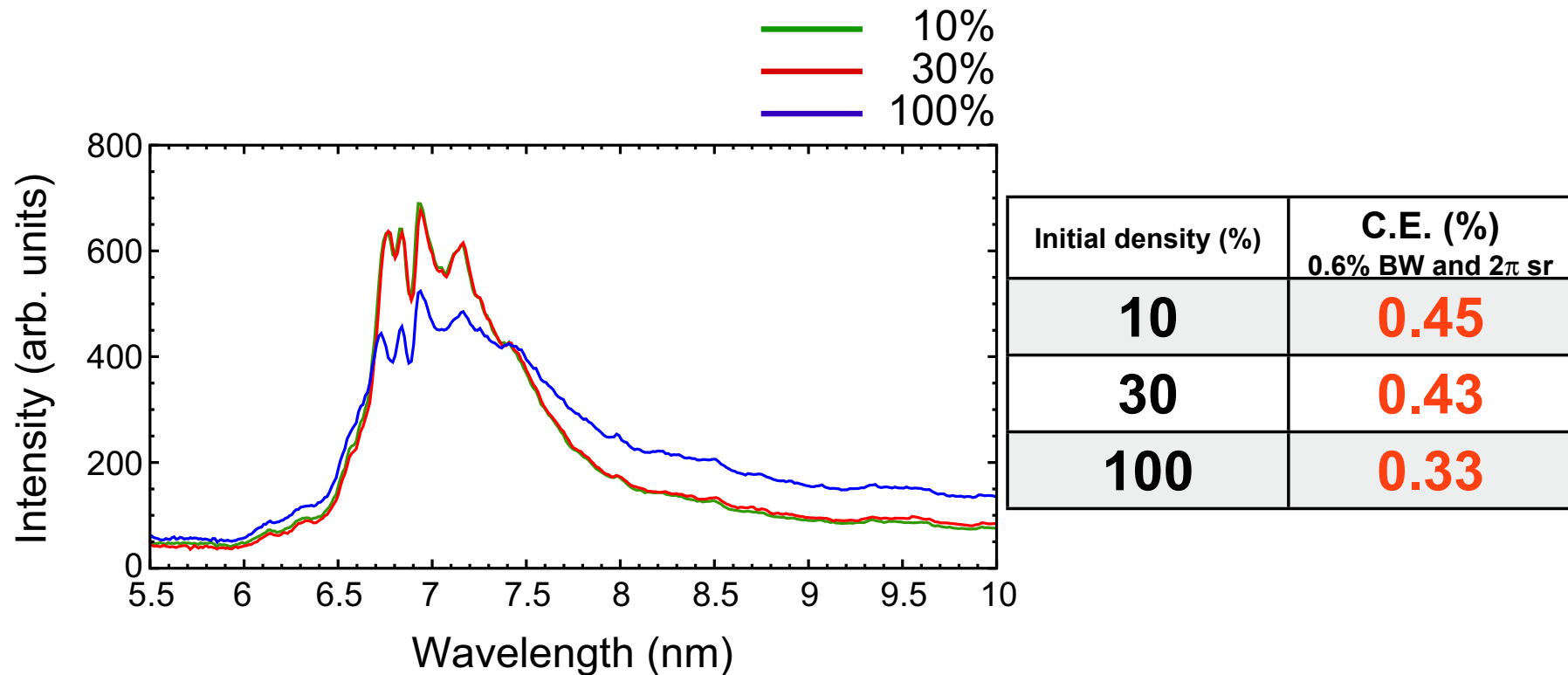
Long wavelength (low critical density): CO₂ laser@10¹⁹ /cc

Low density targets

Short laser pulse duration: ps@YAG laser (1064 nm)

Discharge plasmas (low density plasmas)

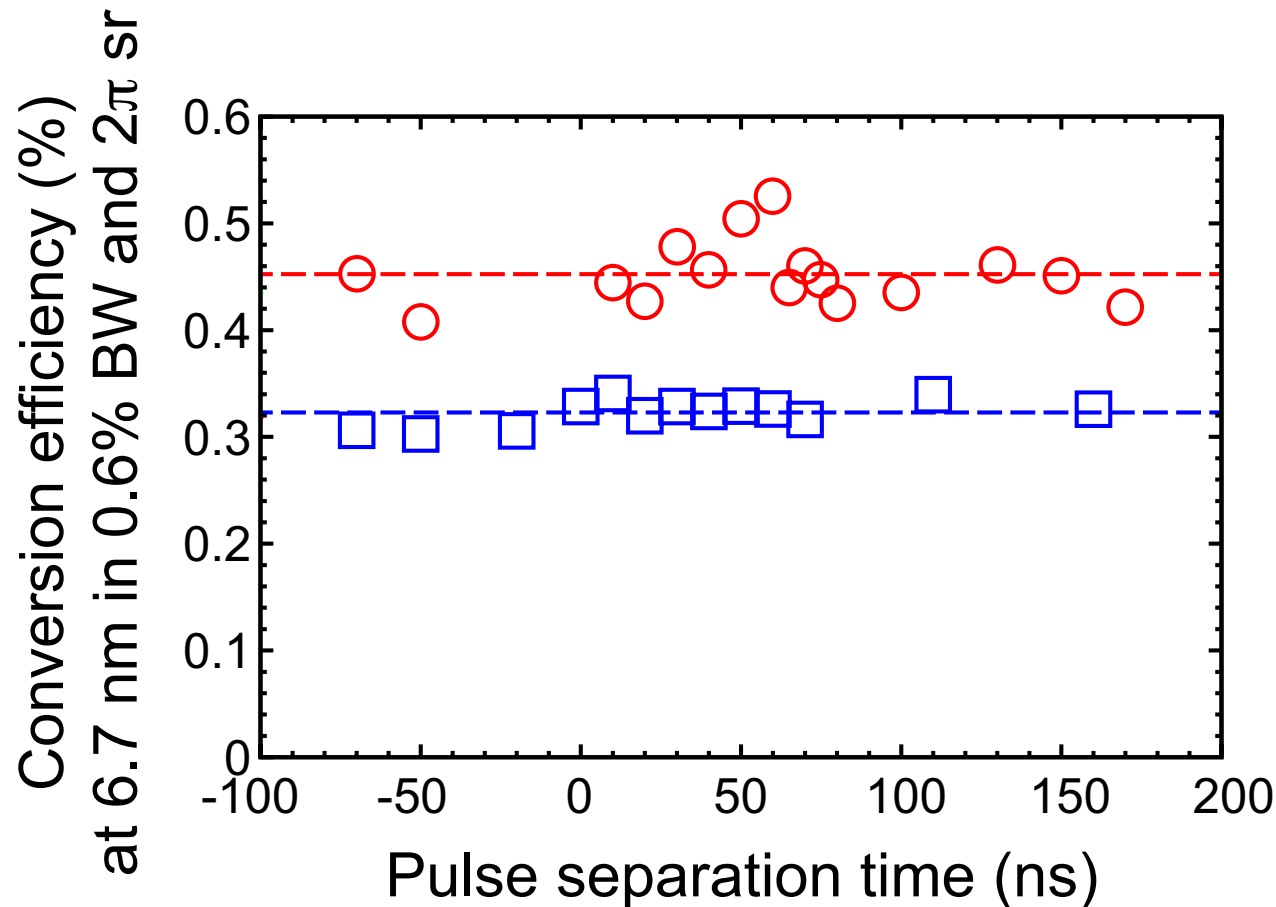
EUV CEs by use of low-initial density targets



Laser intensity: 5.6×10^{12} W/cm²

T. Higashiguchi *et al.*, Appl. Phys. Lett. (accepted for publication).

Enhancement of EUV CE by use of dual laser pulse technique



T. Higashiguchi *et al.*, Appl. Phys. Lett. (accepted for publication).

Physical summary for high-Z plasmas for 6.7-nm Gd plasmas

Optically thin plasmas for reducing self-absorption effects

Suppression of satellite emission & higher spectral purity

Long wavelength (low critical density): CO₂ laser@10¹⁹ /cc

Low density targets

Short laser pulse duration: ps@YAG laser (1064 nm)

Discharge plasmas (low density plasmas)

Discharge experiments

To reduce the satellite lines for low density plasma

Nd:YAG laser

Wavelength: 532 nm

Maximum pulse energy: 1 J

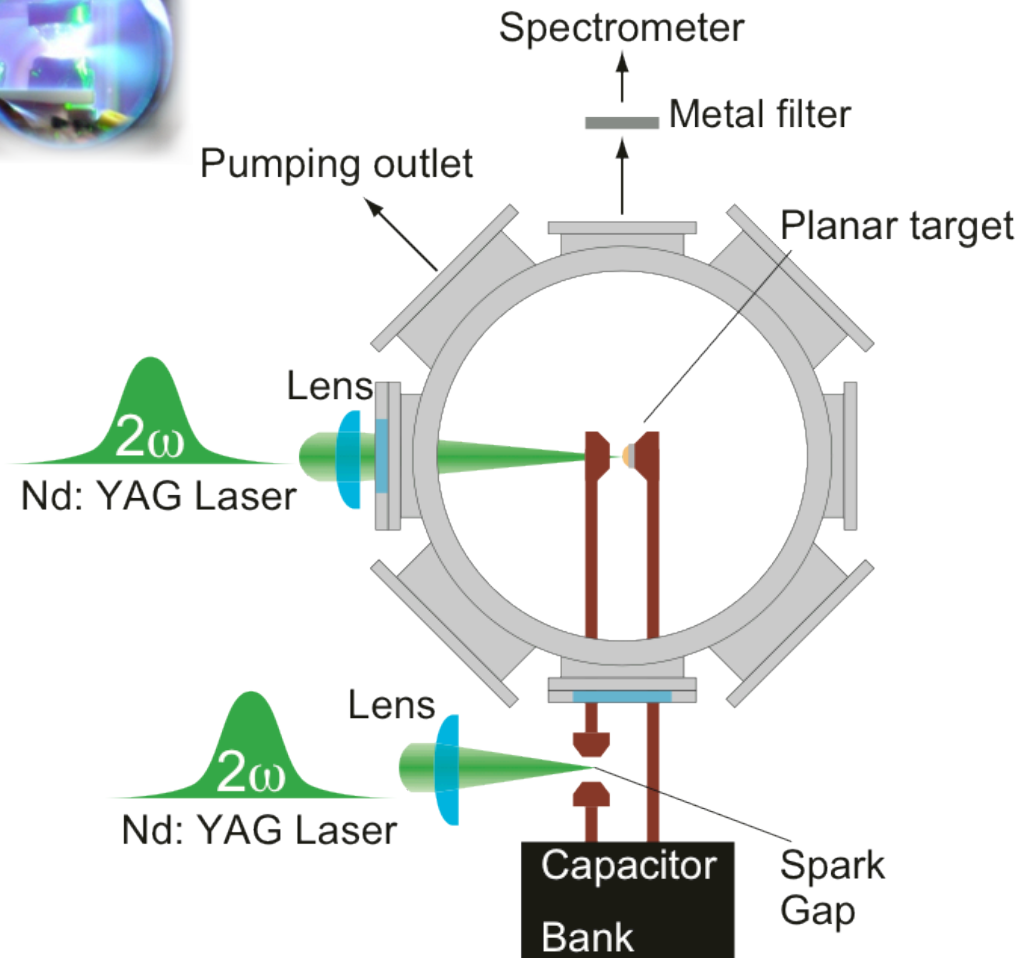
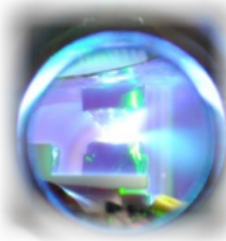
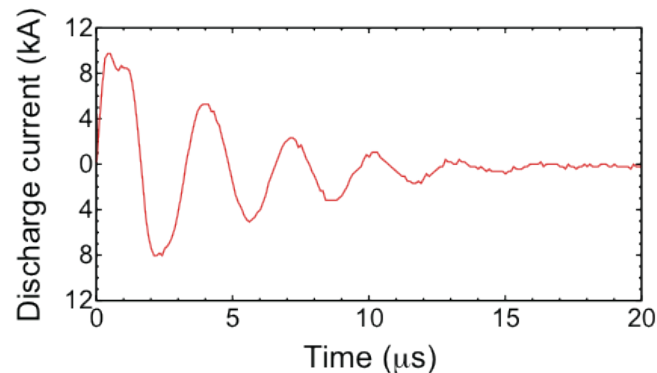
Pulse width: 8 ns (FWHM)

Capacitor: 900 nF

Maximum discharge current: 12 kA

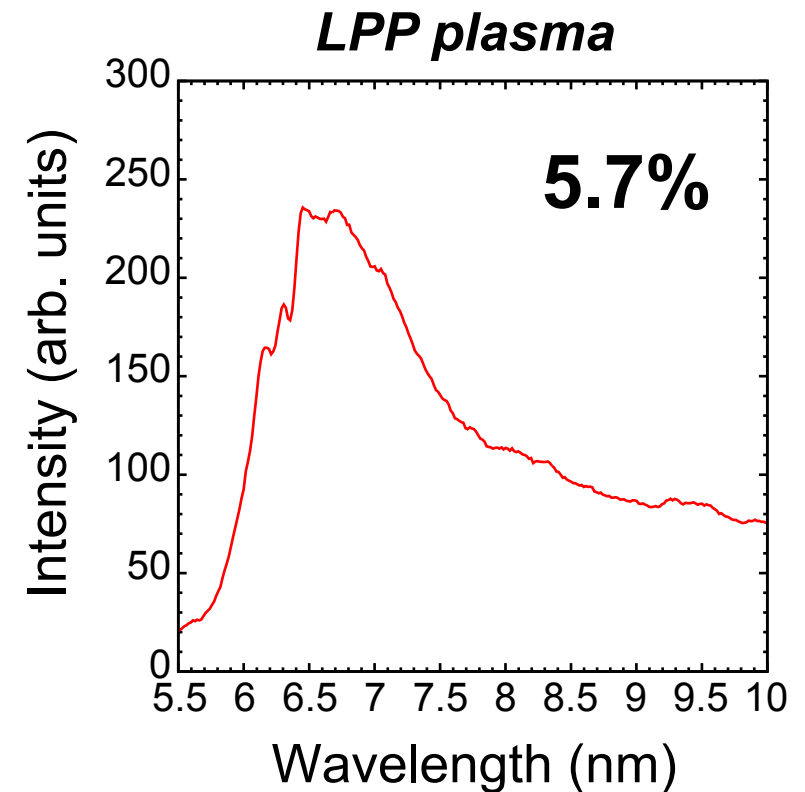
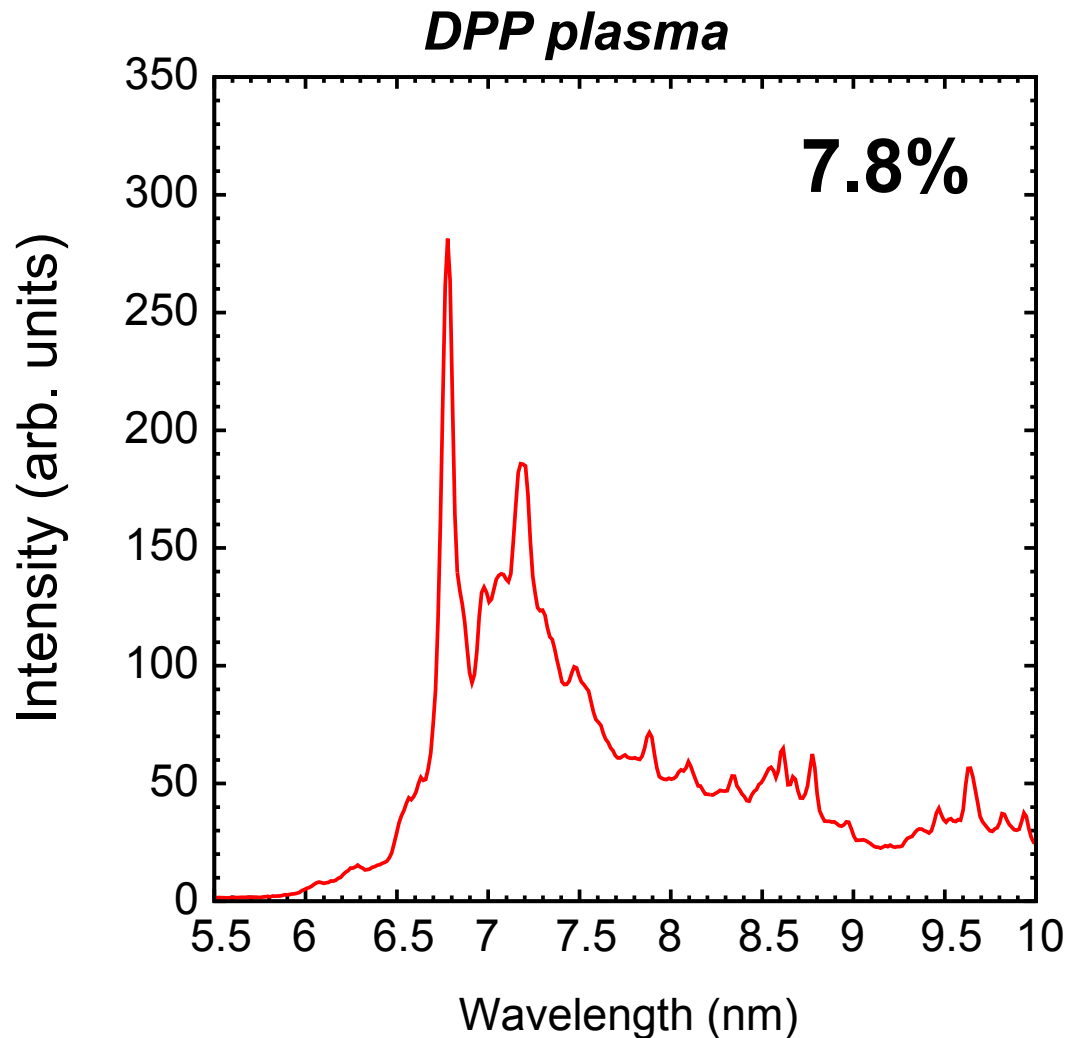
Target: Gadolinium

- Solid density



Discharge experiments

To reduce the satellite lines for low density plasma



Physical summary for high-Z plasmas for 6.7-nm Gd plasmas

Optical thin plasmas for reducing self-absorption effects

Suppression of satellite emission & higher spectral purity

Long wavelength (low critical density): CO₂ laser@10¹⁹ /cc

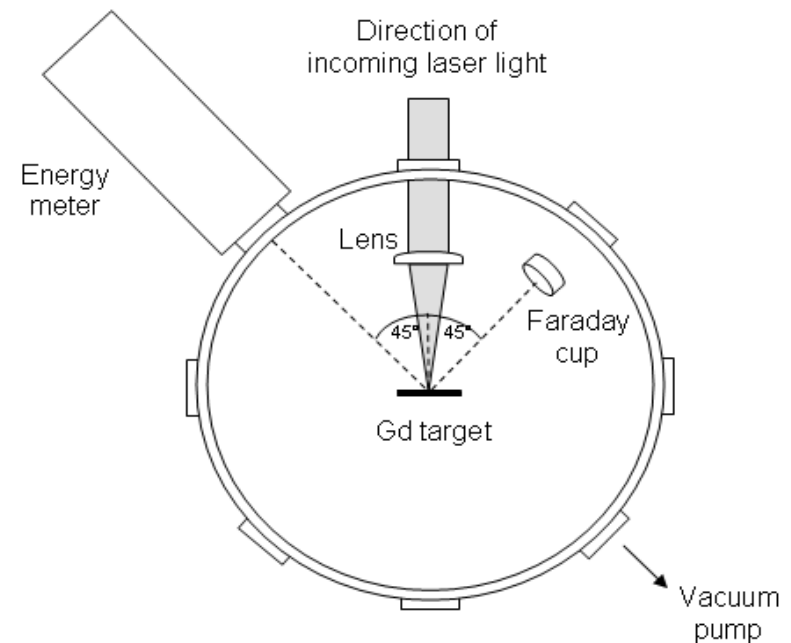
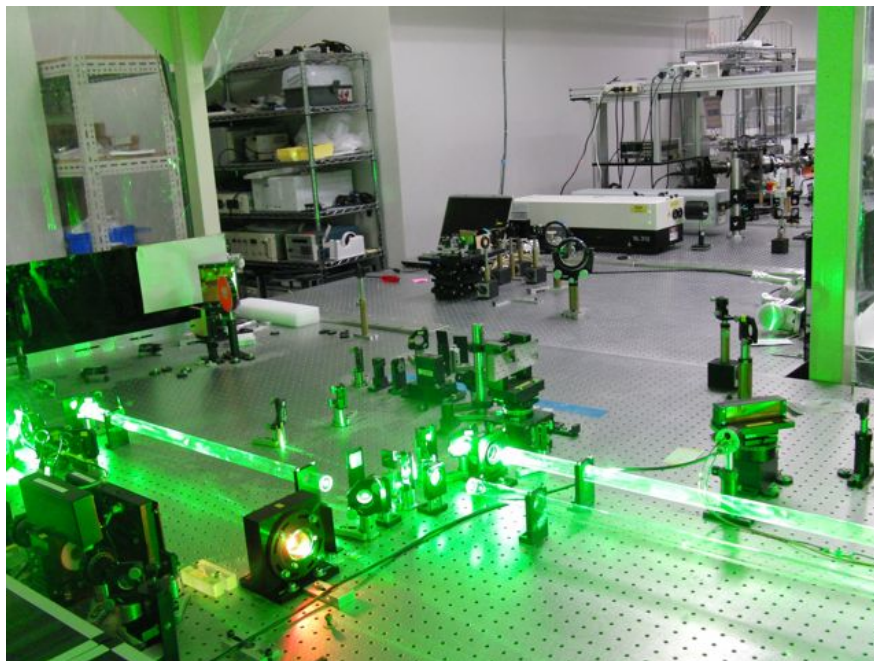
Low density targets

Short laser pulse duration: ps@YAG laser (1064 nm)

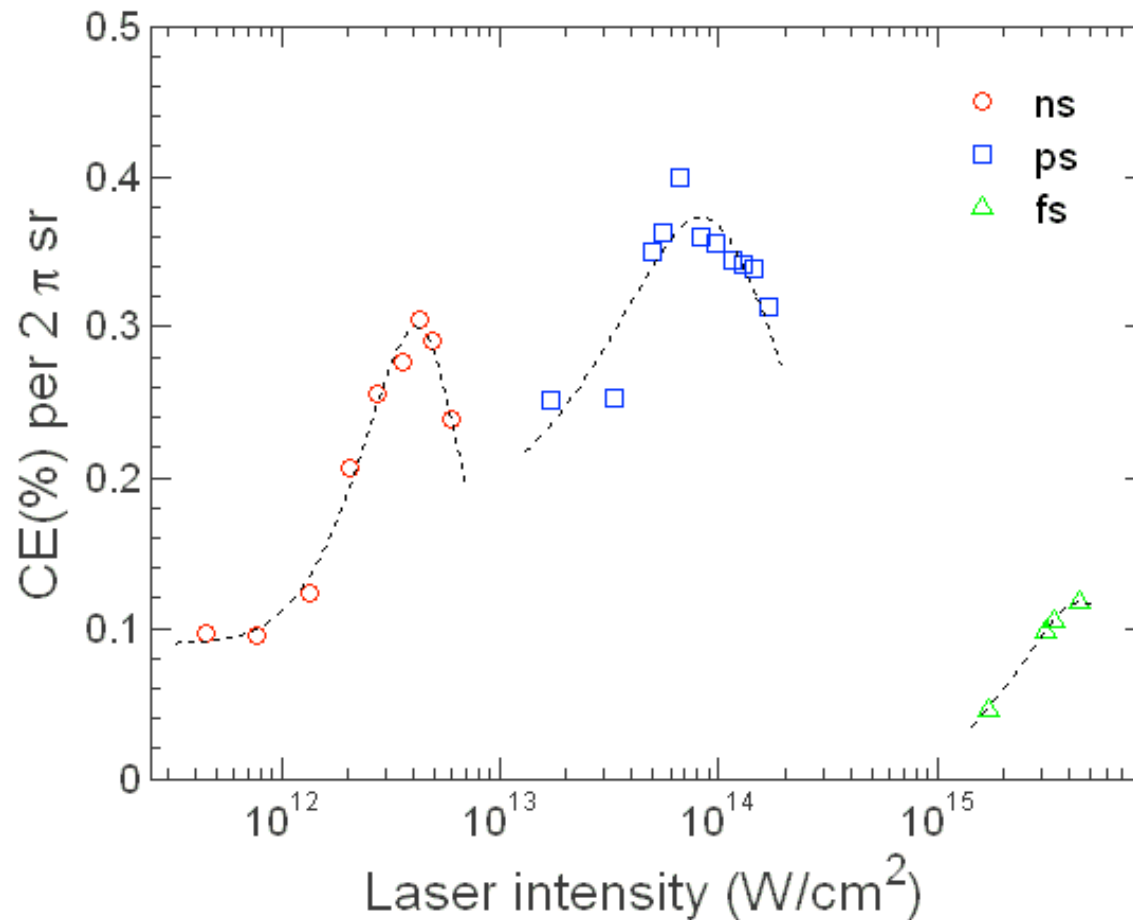
Discharge plasmas (low density plasmas)

Shorter pulse duration effect from fs to ns for Gd plasmas

	τ	λ	E_{\max}
Nd:YAG	10 ns	1064 nm	420 mJ
Nd:YAG	150 ps	1064 nm	210 mJ
Ti:Sapphire*	140 fs	800 nm	30 mJ

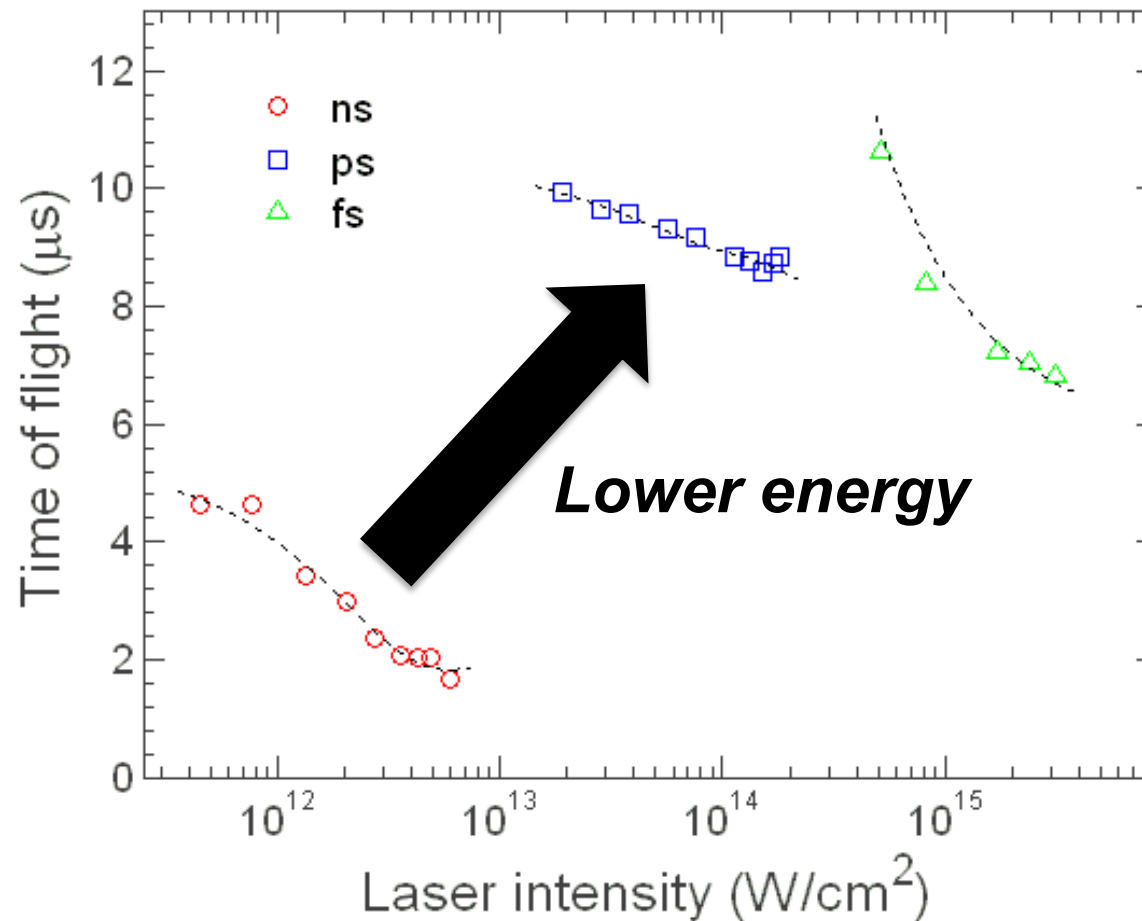


Shorter pulse duration effect from fs to ns for Gd plasmas



T. Cummins *et al.* (submitted).

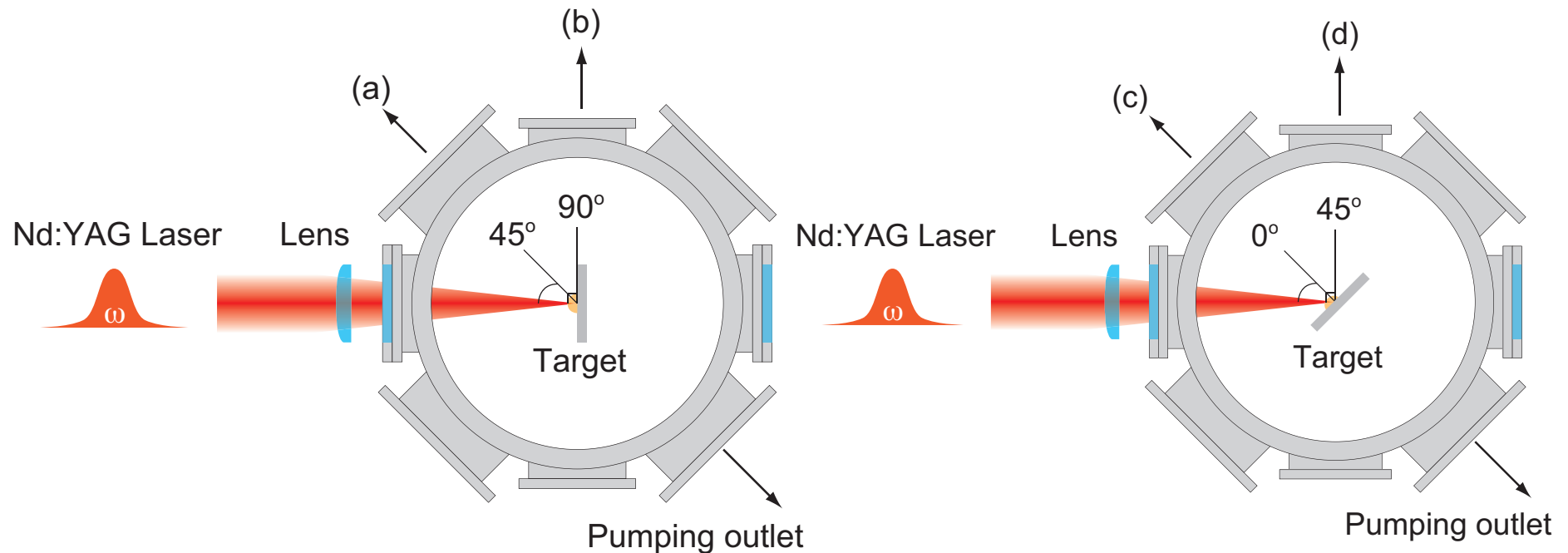
Shorter pulse duration effect Ionic particles



T. Cummins *et al.* (submitted).

Spectral behavior for 10 ns

To couple the modeling

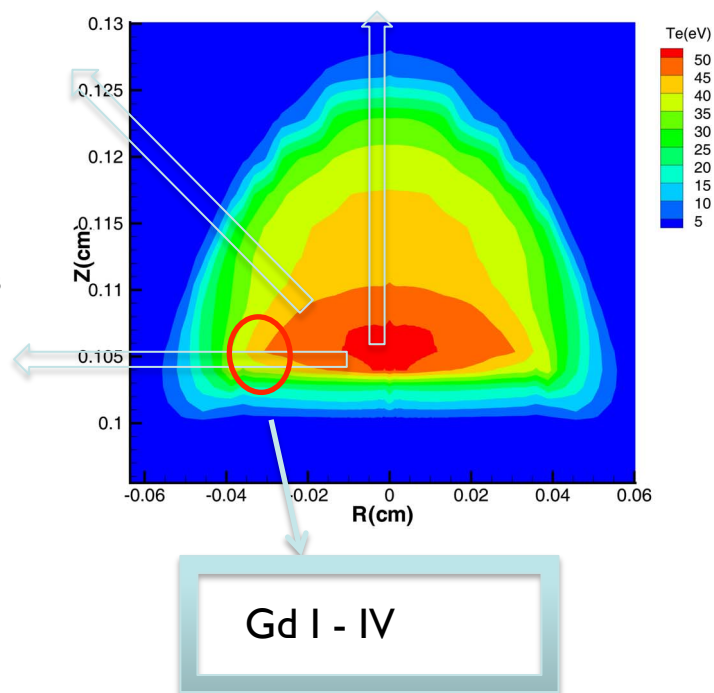
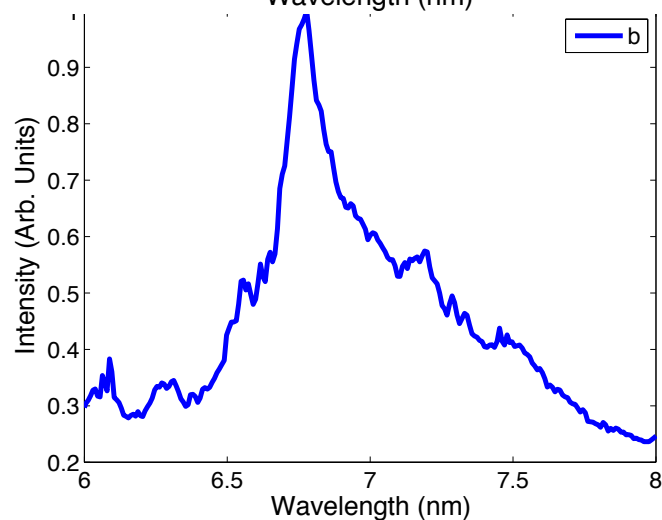
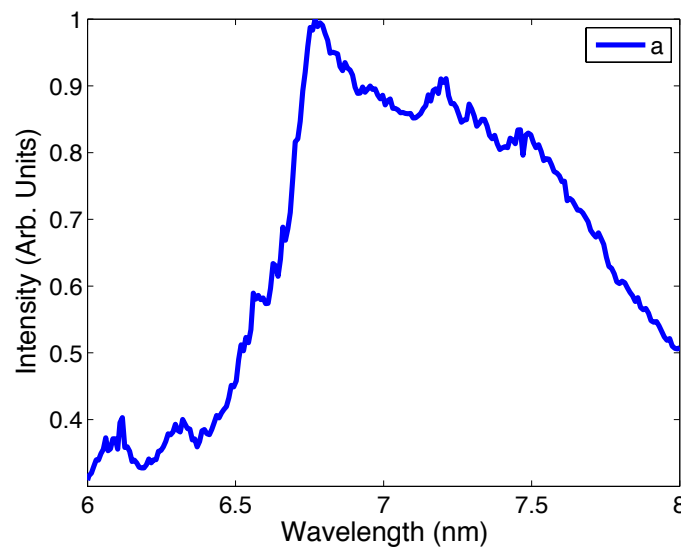


$f = 10 \text{ cm}$, spot size = 30 – 40 μm

$\lambda = 1064 \text{ nm}$

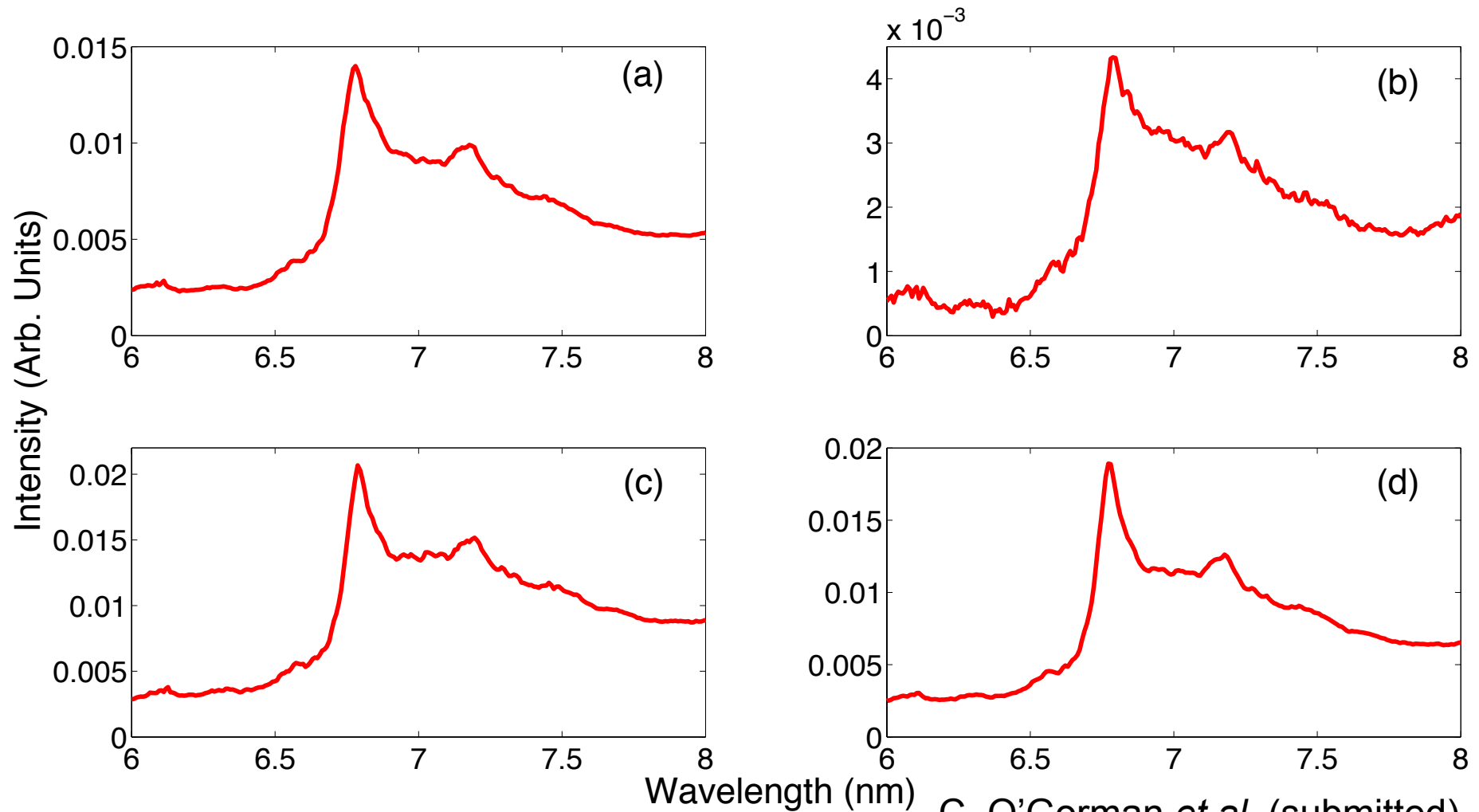
$t = 10 \text{ ns}$ or 150 ps

Spectral behavior for 10 ns Gd plasmas



C. O'Gorman *et al.* (submitted).

Spectral behavior for 150 ps Optical thin Gd plasmas



C. O’Gorman *et al.* (submitted).

Question, issue, and definition...

- CO₂ laser-produced plasma behavior?

When T_e is high, the absorption coefficient is expected to be lower...

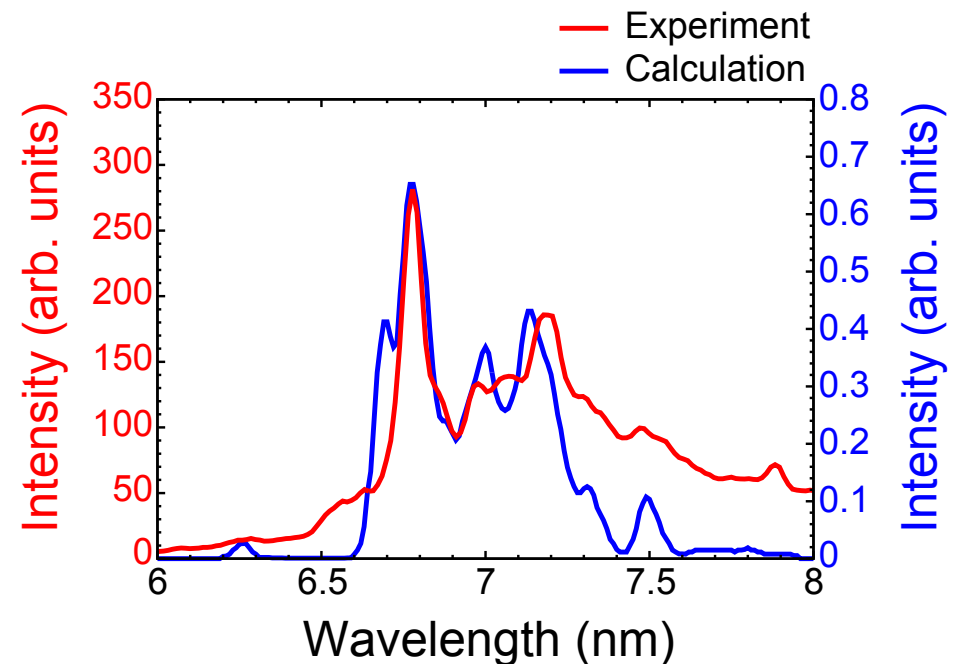
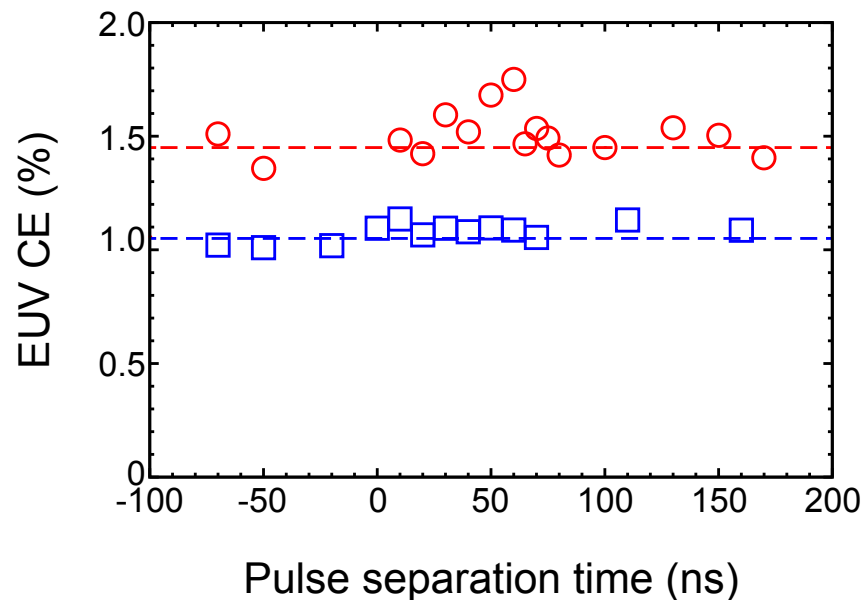
- CE bandwidth (2% to less than 0.6%)

- Regenerative target supply method
(melting point: 1313 °C)

- MLM (optimum incident angle?) design with
wavelength fix of 6.X nm

Main message

- (1) EUV CEs of Sn and Gd plasmas are comparable
(in plasma physics)
- (2) 6.X nm should be defined to be 6.76 nm to design the MLM.



Summary

We have demonstrated the efficient EUV source around 6.7 nm using Gd (rare-earth).

- Low density target to ***suppress the self-absorption*** in plasma
- Conversion efficiency: **~ 0.5-0.6%** before optimizing parameters
- ps laser irradiation for higher CE with low ionic energy
- Spectral behavior at different viewing angle for optical thick ns-LPP
- Question, problem, and definition